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# Packaged, High-Power, Narrow-Linewidth Slab-Coupled Optical Waveguide External Cavity Laser (SCOWECL)

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**Abstract**—We report the demonstration of an InGaAlAs/InP quantum-well, high-power, low-noise packaged semiconductor external cavity laser (ECL) operating at 1550 nm. The laser comprises a double-pass, curved-channel slab-coupled optical waveguide amplifier (SCOWA) coupled to a narrow-bandwidth (2.5 GHz) fiber Bragg grating passive cavity using a lensed-fiber. At a bias current of 4 A, the ECL produces 370 mW of fiber-coupled output power with a Voigt lineshape having Gaussian and Lorentzian linewidths of 35 kHz and 1.75 kHz, respectively, and relative intensity noise < -160 dB/Hz from 200 kHz to 10 GHz.

**Index Terms**—Optical waveguides, power lasers, quantum well lasers, semiconductor lasers

## I. INTRODUCTION

HIGH-POWER, low-noise lasers operating in a single longitudinal mode (single frequency) are important for applications including coherent optical communications, microwave photonics, and optical metrology. For example, in high-performance phase modulated analog photonic systems, high optical powers and narrow linewidths are both critical for achieving high signal-to-noise ratio transmission. For systems operating without use of a balanced photodiode detection scheme, laser relative intensity noise (RIN) becomes a further limitation to the noise figure [1, 2].

In the 1550-nm-wavelength regime, both erbium-doped fiber and semiconductor-based lasers are available as options for meeting the power, noise, and linewidth requirements in optical systems. Fiber lasers have demonstrated power > 200 mW and linewidths < 2 kHz [3]. However, because of the relatively small gain of doped fibers, these lasers are usually long and bulky [4, 5]. This directly leads to higher cost, lower efficiency, and degradation in size, weight, and power (SWaP) performance. In addition, fiber lasers exhibit large relaxation oscillation resonances at low frequencies (0.1-1 MHz). For antenna based applications which operate in the MHz frequency range, the relaxation oscillation noise can greatly degrade system performance. Until recently, semiconductor lasers have either demonstrated high power (> 400 mW) and broad linewidth (~ 1 MHz) [6, 7] or narrow linewidth (< 10 kHz) and lower power (< 10 mW) [8-10]. However, recently a semiconductor distributed feedback laser exhibiting output power ~ 140 mW, relative intensity noise (RIN) ~ -160 dB/Hz, and linewidth ~ 115 kHz has been reported [11]. In this paper, we extend previous designs

of fiber Bragg grating based external cavity lasers [12, 13] to incorporate a novel slab-coupled optical waveguide (SCOW) active section [14, 15]. The SCOW gain medium has low optical confinement ( $\Gamma_{xy} \sim 0.25\%$ ) and large mode dimensions (5 X 7  $\mu\text{m}$ ), enabling high coupling efficiency (~90%) and Watt-class output power. Other notable advantages of the SCOW gain medium are low optical loss (~ 0.5  $\text{cm}^{-1}$ ) and low noise figure (~5.5 dB) [16].

The linewidth of a semiconductor laser can be expressed in the modified form of the Schawlow-Townes equation as [17]

$$\Delta\nu = \frac{v_a (\Gamma_{xy} g_{th})}{4\pi} \left( \frac{1}{N_p V_p} \right) n_{sp} (1 + \alpha_H^2) \left( \frac{n_a L_a}{n_a L_a + n_p L_p} \right)^2 \quad (1)$$

where  $v_a$  is the group velocity of the active region,  $\Gamma_{xy}$  is the cross-sectional confinement factor,  $g_{th}$  is the threshold gain,  $N_p$  is the intracavity photon density,  $V_p$  is the photon cavity volume,  $n_{sp}$  is the population inversion factor,  $\alpha_H$  is the linewidth enhancement factor,  $n_a$  is the active-region group index,  $L_a$  is the length of the active region,  $n_p$  is the passive-region group index, and  $L_p$  is the length of the passive region. Since optical power and loss can be directly related to  $N_p$  and  $g_{th}$ , Eq. (1), shows that the high optical power and low loss properties of the SCOW gain medium are beneficial for obtaining narrow laser linewidths. In addition, using an external passive cavity increases the cavity quality factor and further decreases  $\Delta\nu$ . To decrease  $\alpha_H$ , frequency-selective feedback is used to operate on the blue side of the gain spectrum where  $\alpha_H$  is significantly reduced. In this paper, we demonstrate a packaged SCOW external-cavity laser (SCOWECL) having 370-mW output power, 1.75-kHz Lorentzian linewidth, and < -160-dB/Hz relative intensity noise (RIN).

## II. DEVICE AND PACKAGING DESCRIPTION

The SCOWECL cavity (Fig. 1(a)) comprises a 1-cm-long double-pass curved-channel slab-coupled optical waveguide amplifier (SCOWA), a lensed fiber, a fiber Bragg grating (FBG) ( $\lambda_c = 1550$  nm,  $\Delta\lambda = 20$  pm,  $R = 20\%$ ), and a fiber-pigtailed optical isolator providing 60-dB isolation. Care



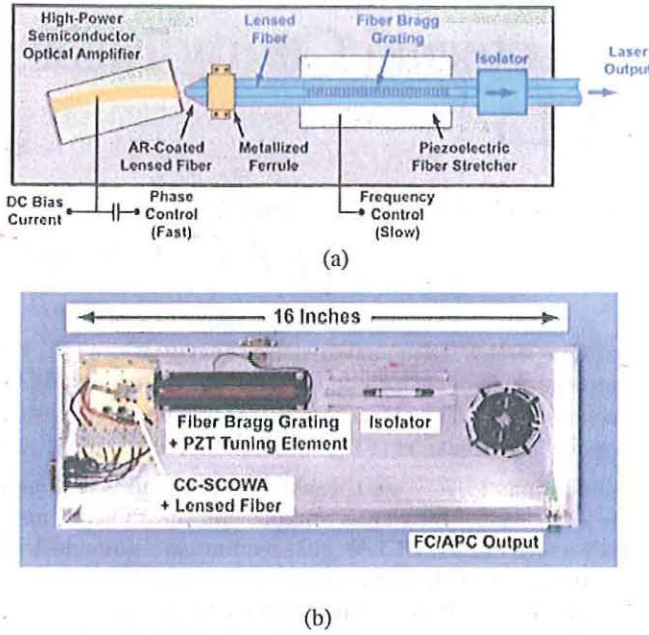


Fig. 1. Packaged 1550-nm SCOWECL: (a) schematic and (b) photograph.

was taken to minimize the length of the external cavity by cleaving the FBG near the edge of the grating and using the smallest length of lensed fiber (3 cm) that could be fusion spliced using available equipment.

The SCOWA material design consists of a 4.6- $\mu\text{m}$ -thick, lightly n-doped InGaAsP waveguide that is weakly coupled ( $\Gamma_{xy} \sim 0.25\%$ ) to an InGaAlAs quantum-well (QW) active region. The active region comprises four 7-nm compressive-strained (+1%) InGaAlAs QWs, three 8-nm tensile-strained (-0.3%,  $\lambda_g = 1240$  nm) InGaAlAs barriers, 12-nm upper and 6-nm lower InGaAlAs bounding layers, and a 15-nm p-doped InAlAs electron-blocking layer. The QW photoluminescence peak  $\lambda = 1565$  nm. The SCOWA was realized by using a curved-channel (10-cm radius) waveguide geometry that provides both a high-reflectivity ( $R > 95\%$ ) flat facet and an anti-reflection-coated, 5-degree-angled facet. The SCOWA was mounted junction-side down to a Cu-W heatsink and temperature controlled using a thermo-electric cooler (TEC). The angled SCOWA facet was coupled to the lensed fiber and affixed using laser welding. The FBG was mounted to a piezoelectric transducer (PZT) to enable wavelength tuning of the Bragg resonance. With the application of 1000 V, the Bragg wavelength red-shifts by 1.1 nm relative to operating conditions at 0 V bias. In the results discussed in the next section, the PZT voltage was maintained at 0 V. Other design and fabrication details can be found in [14, 18].

### III. PACKAGED SCOWECL RESULTS AND ANALYSIS

Figure 2 shows the output power and electrical-to-optical (EO) efficiency of the external cavity laser as a function of

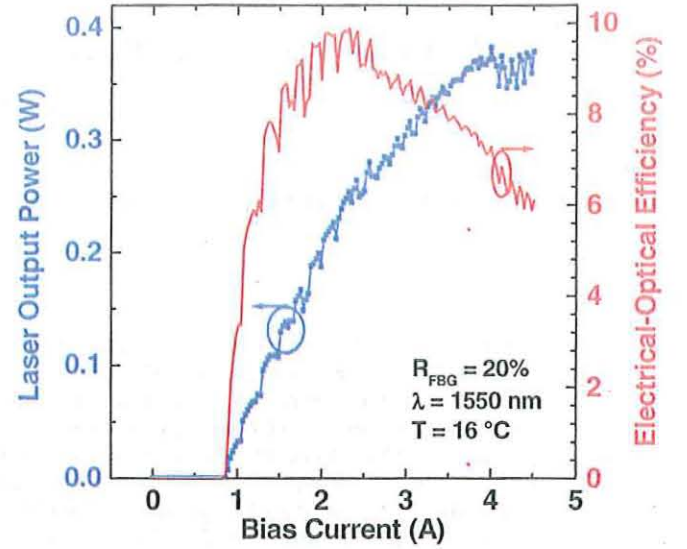


Fig. 2. Output power and electrical-to-optical efficiency characteristics of packaged SCOWECL.

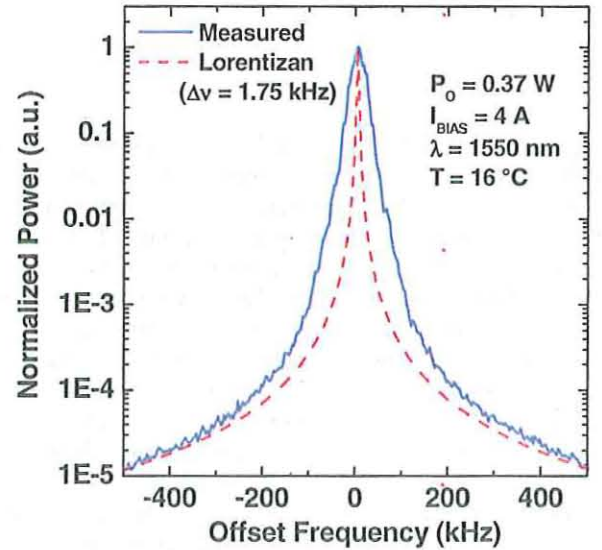


Fig. 3. Spectral lineshape of the packaged SCOWECL measured using the self-heterodyne measurement technique.

current. The power supplied to the TEC was not included in the calculation of the EO efficiency. With the 20% reflectivity FBG, the laser exhibits a threshold of 0.9 A and reaches a CW peak power of 0.37 W at 4 A. The peak efficiency is 10% at 0.25 W and decreases to 7% at 0.37 W. Bench-top testing with the same SCOWA and FBG yielded a maximum power of 0.41 W at 4 A. We attribute the decrease in power of the packaged device to be due to sub-optimal coupling. Modeling of the L-I characteristics has shown the roll-over at high current to be partly due to two photon absorption (TPA) [19]. Thermal effects are believed

to also contribute to the observed decrease in slope

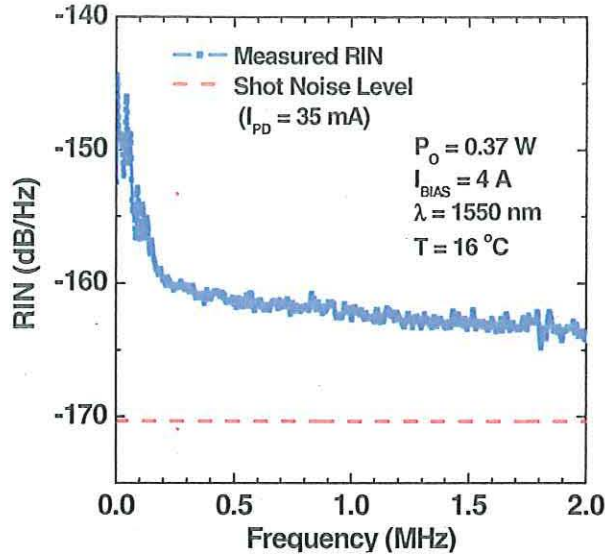


Fig. 4. Low frequency relative intensity noise (RIN) spectrum of the packaged SCOWECL.

efficiency. The jagged peaks in the L-I are attributed to a combination of mode hopping effects and to reflections at the lensed fiber interface.

The lineshape of the packaged SCOWECL, measured using the delayed self-heterodyne technique, is shown in Fig. 3. A 50-km fiber spool was used for delay, and an acousto-optic modulator was used to shift the heterodyne beat to an offset frequency of 35 MHz. Mechanical vibrations and thermal variations were reduced by using a foam-block isolated baseplate and a plexiglass enclosure. The measured lineshape had a Voigt distribution with Lorentzian linewidth  $\Delta\nu_L \sim 1.75$  kHz and Gaussian linewidth  $\Delta\nu_G \sim 35$  kHz.  $\Delta\nu_G$  results from 1/f-noise broadening the lineshape at low offset frequencies and may be reduced with further suppression of external noise sources (power supply, vibrations, thermal fluctuations, etc).

The measured low-frequency (10 kHz-1 MHz) and high-frequency (15 MHz-10 GHz) relative intensity noise (RIN) spectra of the packaged SCOWECL are illustrated in Figs. 4 and 5, respectively. Different photodiodes, RF amplifiers, and electrical spectrum analyzers were used to detect and process the laser signal for the low- and high-frequency measurements. The RIN measurement was calibrated using the RIN transfer standard method [20]. The measured low-frequency results indicate a RIN of -164 dB/Hz near 2 MHz with shot noise at -170 dB/Hz. The high frequency measurements indicate that the laser RIN is below the shot-noise limited floor (-162 dB/Hz). This suggests the side-mode suppression ratio to be  $> 80$  dB. No evidence of relaxation resonance peaks were observed in the bias range tested (1.5 A – 4.5 A). We believe this to be due to long photon lifetimes resulting from a combination of low optical

losses in the SCOWA gain medium and long propagation lengths in the optical cavity.

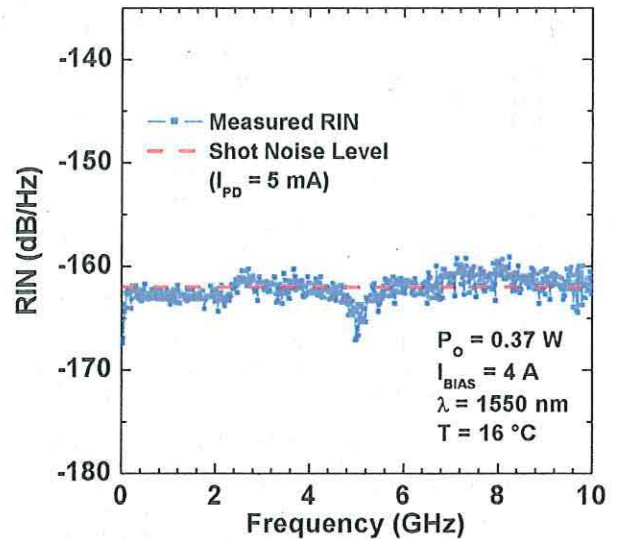


Fig. 5. High-frequency relative intensity noise (RIN) spectrum of the packaged SCOWECL.

#### IV. CONCLUSION

We have demonstrated a packaged high-power, low-noise, narrow-linewidth single frequency external cavity laser based on the slab-coupled optical waveguide concept. The SCOWECL exhibits 0.37 W output power, 1.75 kHz Lorentzian linewidth, and  $< -162$  dB/Hz RIN operating at 1550 nm and 4 A bias. Currently, one of the components limiting the output power of SCOWECLs is TPA. TPA effects can be reduced by increasing the waveguide mode area or by increasing the bandgap of the waveguide beyond twice the photon energy. The SCOWECL is expected to find applications in free space coherent optical communications and in microwave photonic links where high power low noise transmission is critically important.

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